

CLOSED-LOOP PURGING SYSTEM FOR LASER

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TECHNICAL FIELD OF THE INVENTION

The present invention relates generally hermetic sealing of lasers. The invention relates in particular to a closed-loop purging system for water vapor, organic vapor and particulate content in an enclosure surrounding an ultrafast laser resonator or an ultraviolet (UV) laser resonator.

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DISCUSSION OF BACKGROUND ART

Ultrafast lasers are generally regarded as being lasers that deliver output radiation in pulses having a duration of a few hundred femtoseconds or less. One common ultrafast laser is a Ti:sapphire laser, which can be arranged to deliver output radiation at wavelengths between about 700 nanometers (nm) and about 1000 nm. The pulses delivered often have a relatively low energy, for example, tens of millijoules (mJ) to as little as tens of nanojoules (nJ). The short pulse-duration can cause the pulses to have a very high peak power, for example, on the order of gigawatts per square centimeter (GW/cm²) in certain locations in a resonator.

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The very high peak powers delivered by such lasers can rapidly cause damage to

optical components of the lasers, absent measures to inhibit such damage. Laser damage to

optical components may be exacerbated by defects on or in optical surfaces of the

components. Accordingly, it is not unusual that at least some portion of the optical

components of an ultrafast laser are generated by so-called super-polishing techniques

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which yield surfaces having a surface smoothness of atomic dimensions, for example, about

4 Ångstrom Units (Å) root-mean-square (RMS) or less. Optical coatings for such super-

polished components, reflective coatings in particular, are often deposited by ion-beam

sputtering (IBS). IBS is a coating deposition method that can provide coatings having a

high degree of chemical perfection and very low defect content. This minimizes absorption

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and scattering of radiation by the coatings. However, a super-polished, IBS-coated optical

component can be as much as about five or more times more expensive than a similar component polished and coated by more conventional methods. Such additional expense can be wasted if the components are later contaminated by particulate matter, condensates, vapors, or the like.

5 It is not unusual in commercial laser manufacture to assemble lasers in clean-room conditions to minimize particulate deposition on optical components of the lasers. In such a case, it would be usual to place at least the optical resonator of the laser in an enclosure sufficiently sealed to minimize at least ingress of particulate contaminants, and preferably also, ingress of contaminants in gaseous or vapor form. Such an enclosure may be purged, 10 before sealing, with filtered dry nitrogen, dry air or the like.

By implementing one or more above-discussed measures during manufacturing and assembly, an ultrafast laser may be operated for a total as long as several thousand before the performance of the laser becomes significantly diminished by laser damage to one or more optical components thereof. It is believed, however, even if an enclosure could be 15 perfectly hermetically-sealed, damage to optical components may result from contamination of optical components by outgassing products of the optical components, adhesives and the enclosure itself. Outgassing products can be generated while the laser is operating and also while the laser is not operating.

It is believed that the most problematical of the outgassing products are organic 20 vapors, which can be released from material such as adhesives, elastomer seals, and any plastic materials used in the construction of the enclosure. Water vapor may also be released from components of the enclosure or optics therein. The water vapor and the organic vapors can condense directly on surfaces of the optical components. The water vapor and organic vapors together or in combination can react with laser radiation while the 25 laser is operating. Products of the reactions can also condense or be deposited on the optical surfaces. These reaction products may include particulate matter such as carbon particles or soot. Most of these reaction products, if condensed or deposited on the optical surfaces can increase the vulnerability of the optical surfaces to damage by the laser radiation. Even if reaction products were only present within the atmosphere of the enclosure this could still 30 result in unstable operation of the laser.

SUMMARY OF THE INVENTION

The present invention is directed to a method of minimizing contamination of optical components of a laser, the components being located in a gaseous atmosphere within an enclosure. The gaseous atmosphere can contain contaminants including water vapor, 5 organic vapor, and suspended particulate matter. These contaminants may be present at some low level, for example, hundreds of parts per billion or less, immediately after the components are placed in the enclosure. The contaminant level can increase with both operational and non-operational time of the laser.

In one aspect of the present invention, the method comprises extracting gas from the 10 atmosphere within the enclosure. The extracted gas is passed through a first medium selected to reduce the water vapor content of the extracted gas; through a second medium selected to reduce the organic vapor content of the extracted gas; and through a filter selected to reduce the particulate matter content of the extracted gas. After the extracted gas is passed through the first and second media and the filter, it is returned to the enclosure.

15 The extraction and replacement cycle preferably takes place continuously during operation of the laser such that the water vapor, organic vapor, and particulate matter content of the atmosphere in the enclosure is maintained at a minimum consistent with the selection of the media and the filter.

In another aspect of the invention, apparatus for carrying out the method includes a 20 gas conditioning arrangement including the first (a desiccant) medium, the second (a medium for trapping organic vapors) medium, and the filter for trapping particulate matter. The apparatus includes a pump, which is arranged to extract gas from the enclosure and deliver the extracted gas to the gas-conditioning arrangement. The gas conditioning arrangement is configured such that the extracted air delivered thereto by the pump passes 25 through the desiccant medium, the organic vapor trapping medium, and the filter, and is then returned to the enclosure.

In one preferred embodiment, the apparatus further includes first and second valves. The first and second valves are arranged such that a drying gas may be circulated through 30 the desiccant medium for regenerating the desiccant medium while preventing the drying gas from reaching the enclosure.

Maintaining a low organic vapor content in a laser resonator is particularly important if the laser resonator is an ultrafast laser resonator or a laser resonator arranged to generate ultraviolet laser radiation. The relatively high-energy of ultraviolet laser radiation, multiphoton processes in the case of ultrafast lasers, generating longer wavelength radiation 5 can increase the probability of reactions between the laser radiation and the organic vapors or their condensates. As noted above, products of these reactions, including particulate matter, can lead to unstable operation of the laser, or accelerated damage to optical components of the laser resonator.

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BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically illustrates an ultrafast laser including an ultrafast laser resonator, a source of optical pump light, a controller, and a purging system in accordance with the present invention.

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FIG. 2 schematically illustrates details of the laser resonator of FIG. 1, the laser resonator being located in an enclosure cooperative with the purging system of FIG. 1.

FIG. 3 schematically illustrates one preferred embodiment of the purging system of FIG. 1.

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Fig. 4 schematically illustrates another preferred embodiment of the purging system of FIG. 1.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to FIG. 1, laser 20 includes a laser resonator 22, a source 24 of 25 optical pump light, and a purging system 26 in accordance with the present invention. In this example, laser resonator 22 is an ultrafast laser resonator delivering laser radiation in the form of ultrafast output pulses 28. Laser 20 also includes a controller 30 arranged to control operations and parameters the laser resonator, the pump light source, and the purging system. Controller 30 controls operations of purging system 26 via electrical 30 connections 32, 34, and 36. The controller controls operations and parameters of laser

resonator 22 via electrical connections 38, 40, and 42, and controls pump light source 24 via electrical connection 43. Purging system 26 is cooperative with laser resonator 22 via conduits 44 and 46. Purging system 26 also includes conduits 48 and 50, which connect with a desiccant module (not shown in FIG. 1) in the purging system. The function of conduits 48 and 50 is described in detail further to hereinbelow.

Referring now to FIG. 2, laser resonator 22 includes a resonant cavity 52 terminated by mirrors 54 and 56. Mirror 54 is a maximum reflecting mirror. The inclination of mirror 54 can be adjusted by controller 30 via electrical connection 42 and a mirror mount 57 including actuators 58. Mirror 56 is a partially transmitting mirror, which allows output pulses 28 to be delivered from the resonant cavity. A portion of the output pulses is sampled by a beamsplitter 62 and detected by a detector 64. Output of detector 64 is connected to controller 30 by connection 38 for use by the controller in controlling parameters of the laser resonator. The optical path of resonant cavity 54 is folded by fold mirrors 66, 68, 70, and 72. Folding of the optical path reduces the physical length of the resonant cavity.

Resonant cavity 54 includes a gain medium 74 located between mirrors 66 and 70. In this example the gain medium is Ti:sapphire, which provides optical gain in a wavelength region between about 700 and 1000 nanometers (nm). Pump light source 24, in this example, is a frequency-doubled Nd:YVO₄ laser, delivering pump light by fold mirrors a wavelength of 532 nm. Pump light from source 24 is delivered to gain medium 74 through mirror 70. Also located in resonant cavity 52 are two prisms 76 and 78. The prisms are arranged to compensate for group delay dispersion of laser radiation circulating in resonant cavity 52, and are also used to tune the output wavelength of the laser resonator.

Prism 78 is mounted on a movable carrier 80, the movement of which is controlled by controller 30 via electrical connection 40. A slit 81 defines a portion of prism 78 through which optical radiation can pass. The output wavelength of pulses 28 is changed or tuned by operating carrier 80 such that prism 78 is moved to a new location, indicated in FIG. 2 by dotted triangle 78A. Slit 81 is moved synchronously with the prism as indicated by line 81A. Dotted lines 82 indicate a change in optical path in the resonator resulting from the movement of prism 78. Laser resonator 22, in this example, is a mode locked laser

resonator. Mode locking of the laser resonator is effected by an aperture 84 located in resonant cavity 52 and cooperative with a Kerr-lens effect induced in gain medium 74 by pump light delivered from pump-light source (laser) 24.

5 A detailed explanation of operating principles of resonant cavity 52 is not required for understanding principles of the present invention. Accordingly, such an explanation is not presented herein. A detailed explanation of an ultrafast laser including a resonant cavity similar to resonant cavity 52 is provided in co-pending application number 09/813,507 the complete disclosure of which is hereby incorporated by reference.

10 Continuing now with reference to FIG. 2, optical components of laser resonator 22 are located in an enclosure indicated in FIG. 2 by dotted line 90. Pump light from laser 24 enters enclosure 90 via a window 92. Laser output pulses 28 leave the enclosure via a window 94. Other general construction principles of an enclosure such as enclosure 90 are well known to those skilled in the art to which the present invention pertains. Accordingly, such principles are not described or depicted herein. A feature of enclosure 90 specific to 15 the present invention, however, is the connection of the enclosure to conduits 44 and 46, which provide fluid communication between the enclosure and components of purging system 26.

20 The interior (atmosphere) 90A of enclosure 90 is maintained at about ambient atmospheric pressure. The atmosphere of enclosure 90 will usually be an air atmosphere. If enclosure 90 is sufficiently well sealed, however, an atmosphere of nitrogen or some other inert gas may be included. Whatever the gaseous atmosphere of enclosure 90, it can be expected to include some finite level of contaminants, however small that level. As discussed above, these contaminants may include water vapor, organic vapors, and particulate matter. As noted above, particulate matter may include that which was present 25 at the time that the enclosure was closed, and particulate matter generated as a result of interaction between laser radiation circulating in resonant cavity 52 and the organic vapors.

30 Referring now to FIG. 3, one preferred embodiment 26A of a purging system 26 in accordance with the present invention includes a pump 102 and a gas conditioning arrangement 104. Gas conditioning arrangement 104 includes a container 106 containing a desiccant material 108. Desiccant material 108 is preferably silica gel, but maybe any

desiccant material. Gas conditioning arrangement 104 also includes a container 110 including an organic vapor trapping material 112. A preferred organic vapor trapping material is a high surface-area coconut-shell based activated carbon. Organic vapor traps including this material are available in various sizes from Agilent Technologies, Inc. of Palo 5 Alto, California. Other suitable organic vapor trapping materials include a 5 Å molecular sieve.

A filter unit 114 is provided for filtering particulate matter. Filter unit 114 is preferably capable of trapping particles having a size of about 0.5 micrometers (μm) and greater, for example, a HEPA filter. One suitable HEPA filter is available from the Pall 10 Gellman Sciences Inc. of Ann Arbor, Michigan as HEPA Capsule Part No. 12144. This filter has a pore size of 0.3 μm and has a filtering efficiency of 99.97% for 0.3 μm DOP aerosol.

Pump 102 extracts gas from the atmosphere of enclosure 90 via conduit 44. The pump delivers the extracted gas via a conduit 120 and a two-way valve 122 to gas 15 conditioning arrangement 104. The circulation direction of gas through the purging system is indicated in FIG. 3 by arrows A. The gas delivered by pump 102 is urged by the pump through the desiccant material (medium) 108; through a conduit 124; through another two-way valve 126; and then through organic vapor trapping material 112. After passing through the organic vapor trapping material, the gas passes through HEPA filter 114 into 20 conduit 46, which returns the gas to enclosure 90. As noted above, desiccant material 118 reduces the water vapor content of the gas, and organic vapor trapping material 112 reduces the organic vapor content of the gas. HEPA filter 114 reduces the particulate matter content of the gas. Valves 122 and 126 in this mode of operation prevent any of the extracted gas from escaping the purging system via conduits 48 and 50.

25 In one preferred cycle of operation of purging system 26A, the extraction and return of gas from and to the enclosure takes place continually during any period in which laser 20 is operating. Operation of the purging system is started and stopped by correspondingly starting or stopping pump 102 by commands delivered thereto from controller 30 via electrical connection 32. Continuous operation of purging system 26A can provide that in 30 the atmosphere of enclosure 90, the water vapor, organic vapor, and particulate matter

content of the atmosphere are maintained at minimum consistent with the materials and configuration of gas conditioning arrangement 104. It is possible, of course, that the inventive purging system could be activated and deactivated by controller 30 based on measurements of particle count or concentrations of particular vapor species. This, 5 however, would require providing corresponding sensors, which could increase the cost of a laser or the purging system.

After a period of operation, depending on the ambient atmosphere in which laser 20 is located, or the conditions of operation of the laser, desiccant material 108 may become saturated with water vapor. Should this occur, desiccant material 108 may be revived or 10 regenerated by passing a drying gas, such as dry air or dry nitrogen, through the material, as follows.

Operation of pump 102 is stopped. Valve 122 is switched to prevent air from being delivered from pump 102 to the desiccant material, and to allow the drying gas to be delivered to the desiccant material via conduit 48. Valve 126 is switched to prevent any 15 drying gas from reaching enclosure 90 via the organic vapor trapping material, the HEPA filter, and conduit 46. This switching allows drying gas delivered to the desiccant material via conduit 48 to pass through the desiccant material and exit the purging system via conduit 50 as indicated in FIG. 3 by arrows D. After the desiccant material has been regenerated, valves 122 and 126 are switched back to a position that allows gas extracted 20 from enclosure 90 to pass to the gas conditioning system and return to the enclosure via conduit 46. Valves 122 and 126 may be operated by commands delivered thereto along connections 34 and 36 from controller 30.

Another preferred embodiment 26B of a purging system in accordance with the present invention is depicted in FIG. 4. Purging system 26B is similar to purging system 25 26A of FIG. 3 with an exception that desiccant material 108 and organic vapor trapping material 112 are contained in a single container 130. A permeable diaphragm or separator 132 separates the desiccant material from the organic vapor trapping material. One such combined desiccant and organic vapor trapping unit is available from the W.A. Hammond Drierite Company Ltd of Xenia, Ohio as Part No.27068.

It is emphasized here that the sequence of vapor reduction and filtering is particularly important in the method and apparatus of the present invention. If water vapor reduction does not precede organic vapor reduction there could be a significant degradation in the efficiency of organic vapor reduction. As there is a possibility that water vapor 5 removal materials and organic vapor trapping materials can generate particulate matter it is important that particulate matter filtering takes place following water vapor reduction and organic vapor reduction.

In the description of laser 20 given above, laser resonator 22, controller 30, and purging system 26 are described as separate units. This arrangement should not be 10 construed as limiting the present invention. By way of example, as the size of the purging system can be relatively small compared with the laser resonator, the purging system and the laser resonator may be combined in a single unit or housing. Alternatively, the purging system may be combined in a single housing with the controller. In another arrangement, purging system 26 may be configured as a stand-alone module including a dedicated 15 controller separate from controller 30. One skilled in the art to which the present invention pertains may devise other configurations of the purging system, the laser resonator and one or more controllers without departing from the spirit and scope of the present invention.

The purging system of present invention is described above with reference to its use with a Ti:sapphire ultrafast laser. This should not be construed as limiting the present 20 invention. The inventive purging system is applicable to other ultrafast lasers such as those including dyes or semiconductor materials as gain media. As noted above, the very high-power and short duration of ultrafast laser pulses can increase the possibility of the ultrafast laser radiation reacting with any organic contaminants that may be found in the atmosphere in the resonant cavity of the laser. Also as noted above, the inventive purging system is 25 particularly useful in ultraviolet lasers where the high-energy of the ultraviolet radiation also increases the possibility of reactions with any organic contaminants in the laser resonator. Costs permitting, however, it may be found useful to use the inventive purging system with any other laser with the goal of extending the operating lifetime of optical components or reliability of operation of the laser.

The present invention is described above in terms of a preferred and other embodiments. The invention is not limited, however, to the embodiments described and depicted herein. Rather, the invention is limited only by the claims appended hereto.